Hazard Profile - Earthquake

Summary

- The hazard – An earthquake is the sudden release of stored energy that produces a rapid displacement on a fault and radiates seismic waves. Although over a thousand earthquakes are located in Washington each year, only a few have shaking strong enough to be felt by people living here. Infrequently, large earthquakes such as the 2001 Nisqually event, occur that produce very strong ground shaking. This strong shaking causes damage directly and a variety of secondary effects such as ground failure, landslides, and liquefaction.

- Previous occurrences – The Washington coast and the greater Puget Sound Basin are most at risk, though damaging temblors have occurred east of the Cascades. The Puget Sound basin had damaging earthquakes in 1909, 1939, 1946, 1949, 1965, and 2001. Eastern Washington had a large earthquake in 1872 near Lake Chelan and in 1936 near Walla Walla.

- Probability of future events - Because of its location at a convergent continental margin (the collision boundary of two major tectonic plates), Washington State is particularly vulnerable to a variety of earthquakes. FEMA has determined that Washington State ranks second (behind only California) among states most susceptible to damaging earthquakes.

- Jurisdictions at greatest risk – Communities in western Washington, particularly those in the Puget Sound Basin and along the Pacific coast, are most at risk from earthquakes. Some counties in eastern Washington (Chelan, Douglas, Grant, Kittitas, Yakima, Benton, Franklin, Walla Walla, and Spokane) are also vulnerable.

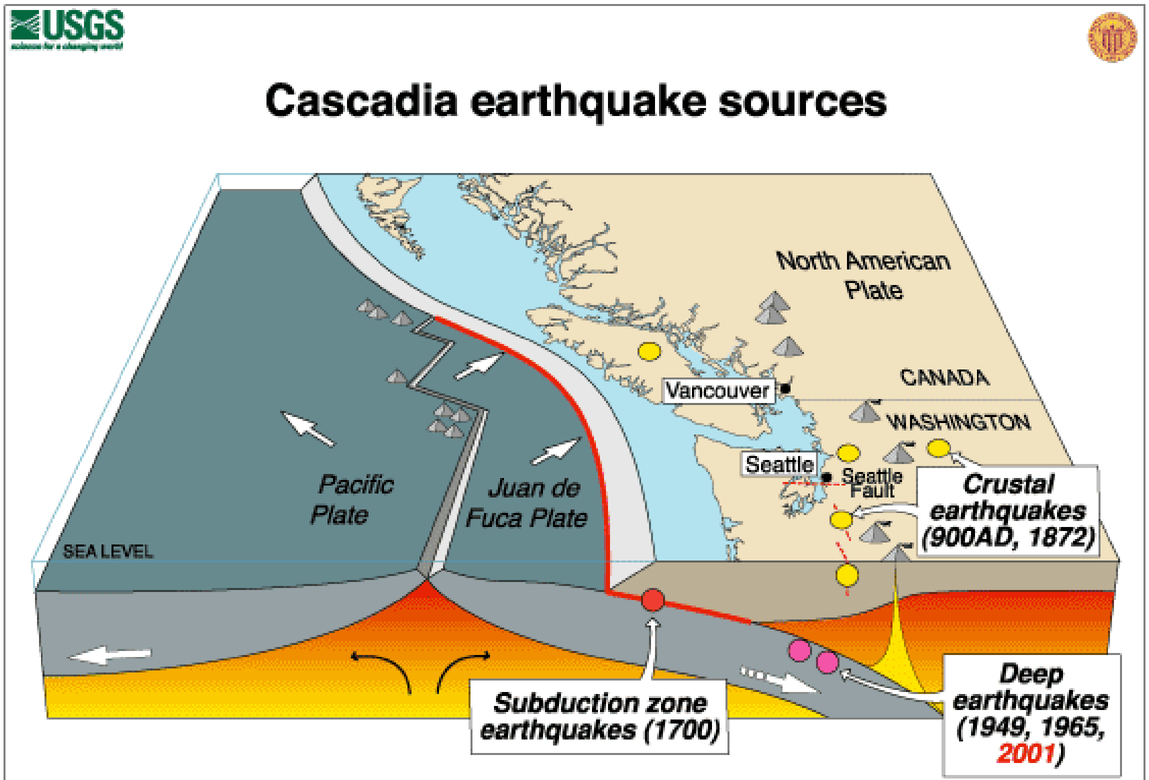
Introduction[1, 2]

An earthquake is the sudden release of stored energy that produces a rapid displacement on a fault and radiates seismic waves. Although over a thousand earthquakes are located in Washington each year, most produce ground shaking that is too small to be felt. Occasionally large earthquakes produce very strong ground shaking. It is this strong shaking and its consequences – ground failure, landslides, liquefaction – that damages buildings and structures and upsets the regional economy.

Washington, especially the Puget Sound basin, has a history of relatively frequent damaging earthquakes. Large earthquakes in 1946 (magnitude 5.8), 1949 (magnitude 7.1) and 1965 (magnitude 6.5) killed 15 people and caused more than $200 million (1984 dollars) in damage throughout several counties. The state experienced at least 20 damaging events in the last 125 years.

The Nisqually earthquake on February 28, 2001 is the most recent damaging earthquake. This was a deep earthquake of magnitude 6.8 earthquake. It was centered about 10 miles northeast of Olympia and at a depth of about 30 miles. One person died of a heart attack, more than 700 people were injured, and various estimates place damage at between $1 billion and $4 billion; exact figures are not available, as insurance claims information is not available.

Washington's earthquake hazards reflect its tectonic setting. The Pacific Northwest is at a convergent margin between two tectonic plates of the Earth's crust. The Cascadia subduction zone is the long fault boundary between the continental North America plate and the oceanic Juan de Fuca plate that lies offshore from northern California to southern British Columbia. The two plates are converging at a rate of about 2 inches per year. The interaction between these two plates creates a complicated system of three distinct earthquake source zones. The earthquakes produced by each source zone are responsible for the earthquake hazards across Washington.



Source	Affected area	Max. Size	Recurrence
Subduction Zone	W.WA, OR, CA	M 9	500-600 yr
Deep Juan de Fuca plate	W.WA, OR,	M 7+	30-50 yr
Crustal faults	WA, OR, CA	M 7+	Hundreds of yr?

Figure 1. Earthquake source zones for Washington with maximum earthquake magnitude and estimated recurrence time.

The first source zone is the Cascadia subduction zone; the long fault boundary between the North American and Juan de Fuca plate (see Figure 1). This source zone produces great earthquakes, similar to the 2004 Indonesian earthquake, about every 500 years. Most of the fault area is offshore, so most of the ground shaking effects are expected in western Washington. As the Juan de Fuca plate subducts (slides) beneath North America, the plate begins to bend more steeply into the earth. The area near this bend is the second source zone, usually called the deep (Benioff) zone. This is the most frequent source of damaging earthquakes for Puget Sound; the 2001 Nisqually earthquake was in this source zone. The third zone is the earth's shallow crust and is the most poorly understood of the three source zones. Since 2000, geologists have discovered over 12 active crustal faults in Puget Sound, but few are documented in other parts of the state.

Because the earthquake sources are not uniform, the earthquake threat in Washington is also not uniform. The United States Geological Survey (USGS) produces uniform probabilistic seismic hazard maps for the United States. The map for Oregon and Washington in Figure 2 shows the probability of exceeding the plotted ground motion values in 50 years. For hazard mitigation planning purposes, we can consider the brown and red colors areas as highest hazard and areas of light blue to be lower hazard. The curves shown in Figure 2 reflect the hazard zones in Figure 1. The highest hazard is along the Washington coast—these areas are immediately above the Cascadia subduction zone. Moving inland, the contours bend inland around the greater Puget Sound area from about the Columbia River; this bending is largely due to the hazard from deep earthquakes like the 2001 Nisqually earthquake. Generally, the effect of crustal faults is muted because they are poorly defined; however, these earthquakes are the most damaging due to their proximity to the earth's surface. Two notable exceptions are the bubble of higher hazard (red color) over the Seattle fault and the southern Whidbey Island fault in Puget Sound. While most earthquakes occur in Western Washington, earthquake hazards are significant east of the Cascades to about the Columbia River. The green area to the west of the Columbia shows acceleration values comparable to those seen over portions of western Washington in the Nisqually earthquake.

Understanding local earthquake hazards requires understanding of how each of the three source zones will affect individual localities. West of the Cascade Mountains, all three source zones combine to determine local hazards. East of the Cascade Mountains will usually not be affected by ground shaking from deep earthquakes due to the manner in which seismic waves travel greater distances, and, therefore, most structures will likely show minimal effects from Cascadia ground shaking. However, certain large structures in eastern Washington, such as dams and bridges, may be vulnerable to very long period shaking expected from a Cascadia earthquake. Crustal (shallow) faults, which are closer to the surface, are located throughout the entire state, and can produce intense, localized ground shaking.

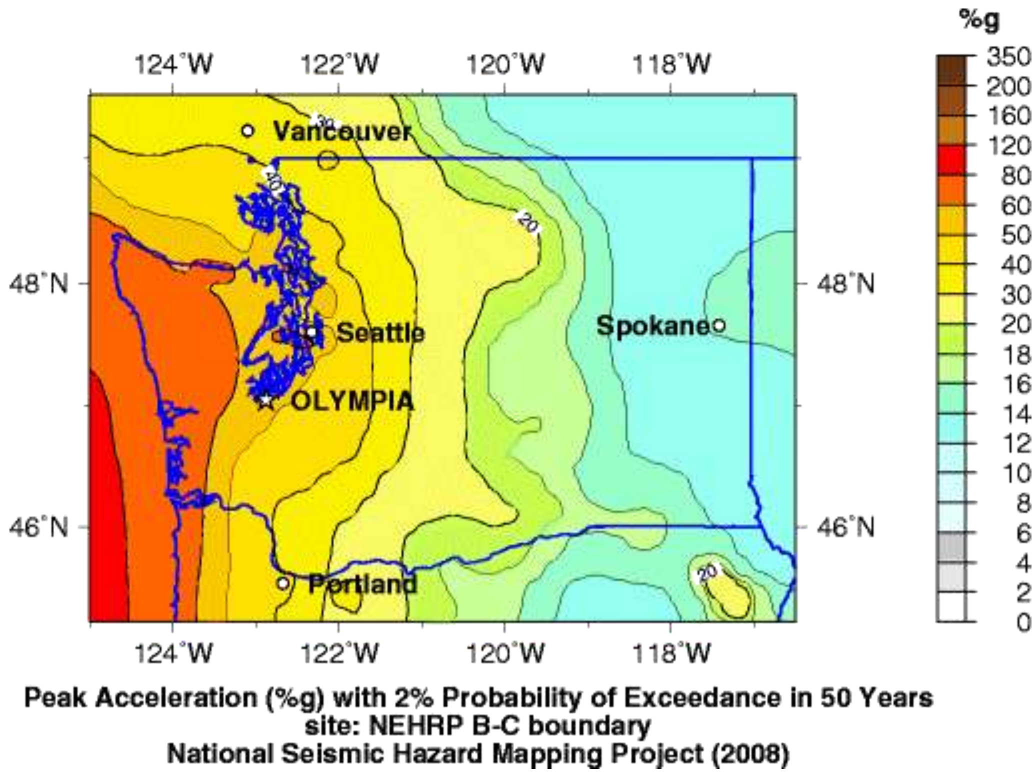


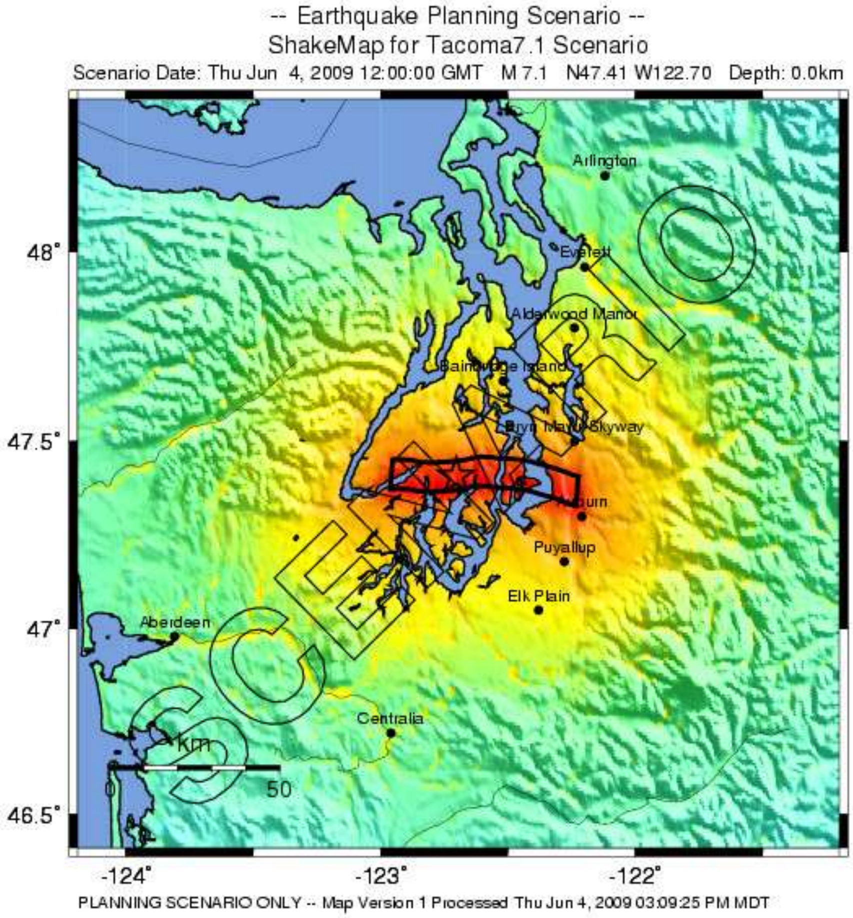
Figure 2. Peak ground acceleration values with a 2% chance of exceeding that value in 50 years. Red and brown colors are very high ground shaking; light blue is lower expected accelerations. Source: USGS at http://earthquake.usgs.gov/earthquakes/states/washington/hazards.php

Although the probabilistic map in Figure 2 is the primary input to the International Building Code and the code governing highway construction, it is sometimes useful to consider the effects from an individual fault. This requires calculating "deterministic" ground motion models. For a deterministic model, seismologists calculate the expected ground shaking but don't consider how often the earthquake may occur. They pick reasonable faulting parameters and generally use a known fault. The USGS, Washington Department of Natural Resources, and Washington Emergency Management produced a series of 15 deterministic ground motion models (Table 1) for selected shallow faults, deep earthquakes, and the Cascadia subduction zone. Again, these deterministic models ignore the likelihood of an earthquake occurring, but focus on the shaking expected should such an event occur. While many of these scenario models are centered on known faults, some events have been developed for research purposes. Some of these ground motion models are available at:
http://earthquake.usgs.gov/eqcenter/shakemap/list.php?s=1&y=2009

Table 1: Deterministic Ground Motion Models for Selected Sources			
Scenario	Magnitude	Basis	Source zone
Boulder Creek	6.8	Trenching	Crustal
Canyon River-Price Lake	7.4	Trenching	Crustal
Chelan	7.1	Scenario: Not on a known fault	Crustal
Cle Elum	6.8	Scenario: Not on a known fault	Crustal
Lake Creek fault	6,8	Trenching	Crustal
Mill Creek (Toppenish Ridge)	7.1	Scenario weakly based on trenching, known fault	Crustal
Saddle Mountains (eastern WA)	7.35	Trenching	Crustal
St. Helens Seismic zone	7.0	Seismicity	Crustal
Seattle fault	6.7	Trenching, uplift	Crustal
Southern Whidbey Island fault	7.4	Trenching, uplift	Crustal
Spokane	5.5	Seismicity, not on a known fault	Crustal
Tacoma	7.1	Trenching, uplift	Crustal
Cascadia	9.0	Paleoseismology	Subduction
Nisqually	7.2	Historical seismicity	Deep
Seattle-Tacoma	7.2	Historical seismicity	Deep

Generally, most of these ground motion models are considered well determined. Faults with estimates based on trenching (and in some cases uplift of coastal features) have at least some known history of movement. Likewise, the models for the two deep events are very well constrained, in part because of their familiar occurrence in Puget Sound. The parameters used to model Cascadia are well constrained, but certain characteristics of the ground motion (such as duration of strong shaking and the effect on long or tall structures) are not modeled. In some cases, such as Chelan, the historical record documents a strong earthquake, but the actual fault and fault parameters are still not known. The same is true for the Spokane models. Finally, the Mill Creek and Saddle Mountain scenarios are based on limited trenching but the fault traces themselves are known.

The Tacoma fault scenario (Figure 3) is an example of these new deterministic maps. For this map, seismologists picked specific traces of the mapped fault to break during an earthquake. With the fault trace and the magnitude of 7.1, seismologists then estimated the length of the fault, the depth of the fault, its orientation in the earth, how much the fault moves to calculate the ground motions. The ground motions attenuate as they move away from the source and then are usually amplified by local geologic site conditions as the seismic waves reach the earth's surface.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 3: Tacoma fault scenario. This is a deterministic model, as opposed to the probabilistic hazard maps in Figure 2. This map is for a single fault and does not represent the entire earthquake hazard in nearby communities.

Deep or Benioff Zone Earthquakes[3]

Deep or Benioff Zone earthquakes occur within the subducting Juan de Fuca plate at depths of 15 to 60 miles, although the largest events typically occur at depths of about 25 to 40 miles. Until recently the Olympia quake in 1949 was thought to be the largest of these deep earthquakes. The USGS recalculated this event, changing the magnitude from the original 7.1 to 6.8, the same size as the 2001 Nisqually event. Other significant Benioff zone events include the magnitude 6.5 Seattle-Tacoma quake in 1965, the magnitude 5.8 Satsop quake in 1999, and the magnitude 6.8 Nisqually quake of 2001. Strong shaking during the 1949 Olympia earthquake lasted about 20 seconds; during the 2001 Nisqually earthquake, about 15 to 20 seconds.

The probability of future occurrence for earthquakes similar to the 1965 magnitude 6.5 Seattle-Tacoma event and the 2001 magnitude 6.8 Nisqually event is about once every 35 years. The USGS has estimated that there is an 84% chance of a magnitude 6.5 or greater deep earthquake over the next 50 years.

Subduction Zone (Interplate) Earthquakes[4]

Subduction zone or interplate earthquakes occur along the interface between tectonic plates. Scientists have found evidence of great-magnitude earthquakes along the Cascadia Subduction Zone. These earthquakes are very powerful, with a magnitude of 8 to 9 or greater; they have occurred at intervals ranging from as few as about 100 years to as long as 1,100 years. The last of these great earthquakes struck Washington in 1700. Scientists currently estimate that a magnitude 9 earthquake in the Cascadia Subduction Zone occurs about once every 500 years.[5]

Subduction zone earthquakes are particularly dangerous in that they produce strong ground motions and in nearly all cases, damaging tsunamis. Along the Washington coast, the brown colors in Figure 2 indicate that very strong shaking is anticipated there. Along the I-5 corridor ground shaking will be attenuated by the greater distance from the source zone, but significant damage will result. Tall buildings and long bridges may be especially susceptible to long-period ground shaking produced on the subduction zone. Finally, the long-period motions may affect large structures in eastern Washington as well and can generate seiches in susceptible water bodies.

Shallow or crustal Earthquakes[6]

Shallow earthquakes occur in the earth’s crust within the upper part of the North American plate (Figure 1). Although there are numerous examples of moderate magnitude shallow earthquakes occurring in Washington, most of these events cannot be directly related to an individual fault. Recent examples in western Washington an earthquake near Duvall in 1996, off Maury Island in 1995, near Deming in 1990, near North Bend in 1945, just north of Portland in 1962, and at Elk Lake on the St. Helens seismic zone (a fault zone running north-northwest through Mount St. Helens) in 1981. These earthquakes had a magnitude of 5 to 5.5.

The 1872 earthquake near Lake Chelan was the state's most widely felt shallow earthquake. The magnitude for this event has been estimated at 6.8. The 1936 magnitude 6.1 earthquake near Walla Walla was also a shallow event. Because of their remote locations damage was light from these two quakes.

Of the three earthquake sources, the shallow zone is the least understood. Until 2000, earth scientists had not located a fault trace, where deformation breaks to the surface, anywhere in the Puget lowlands. Without knowing the location of fault traces, geologists were unable to determine how often faults moved and how large to expect the events. This has changed dramatically in the last 9 years, with paleoseismologists documenting at least 12 major faults with recent motion in the Puget Sound region. A systematic assessment of earthquake hazards in eastern Washington started in 2008. The findings of ongoing research on surface faults (see below) may lead to an assessment of greater earthquake risk in parts of Washington.

Puget Lowland[7, 8, 9, 10, 11]

Recent geologic studies have greatly enhanced scientists' ability to locate and study active faults, particularly in the Puget Sound basin. Using a combination of aeromagnetic surveys, high-resolution light detecting and ranging data (LiDAR), and geological field investigation, studies have documented about a dozen active faults or fault zones in the greater Puget Sound basin (Figure 4). Field evidence shows magnitude 7 or greater earthquakes occurred on at least eight of these faults. These faults include: the Seattle fault, Tacoma fault, Darrington-Devils Mountain fault, Utsalady Point fault, Southern Whidbey Island fault, Frigid Creek fault, Canyon River fault and the Lake Creek fault.

While investigation continues on Puget Lowland faults in an effort to better define the recurrence and magnitude, scientists already have learned much about them. For example, evidence points to a magnitude 7 or greater earthquake on the Seattle fault about 900 A.D. Such evidence includes a tsunami deposit in Puget Sound, landslides in Lake Washington, rockslides on nearby mountains, and a seven-meter uplift of a marine terrace.

An earthquake with such a magnitude today would cause tremendous damage and economic disruption throughout the central Puget Sound region. Using estimates of damage and loss developed in the scenario for a magnitude 6.7 event on the Seattle fault showed such a quake would result in extensive or complete damage to more than 58,000 buildings with a loss of $36 billion, more than 55,000 displaced households, and up to 2,400 deaths and 800 injuries requiring hospitalization. Although losses would likely be less from similar earthquakes on other Puget Sound faults away from the core of the Seattle urban area, all of the newly defined active faults represent the possibility of very high damage, loss of life, and major economic impact.

Scientists currently estimate the approximate recurrence rate of a magnitude 6.5 or greater earthquake on the Seattle Fault at about once every 1,000 years and for an earthquake of this magnitude anywhere on a fault in the Puget Sound basin to be once in about 350 years.

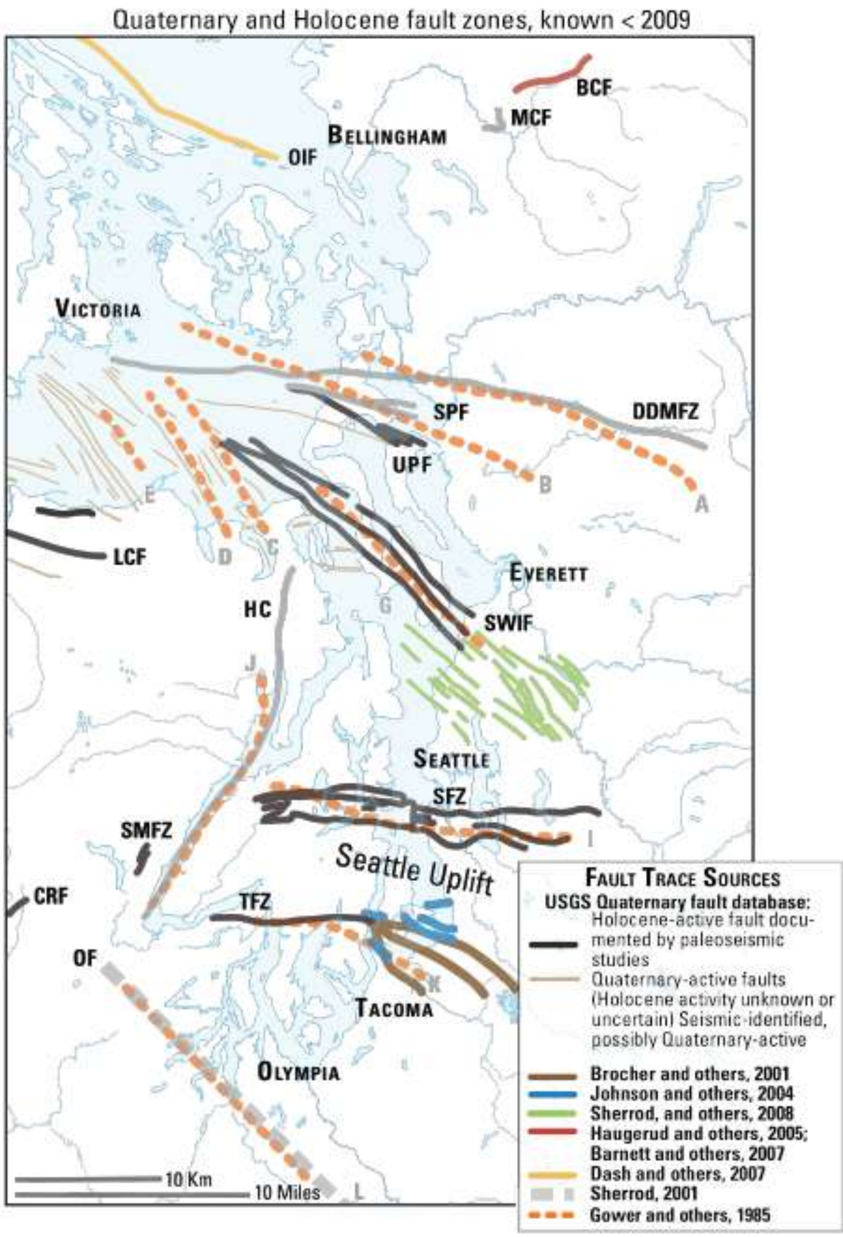


Figure 4. Known earthquake crustal faults in the greater Puget Sound area. The map shows the location of faults under study by earth scientists. Active faults as determined by documented evidence of Holocene surface deformation or surface rupture are abbreviated as: BCF, Boulder Creek fault; OIF, Outer Island fault, DDMFX, Devils Mountain-Darrington fault zone, UPF, Utsalady Point fault; LCF, Lake Creek fault, SWIF, Southern Whidbey Island fault; SFZ, Seattle fault zone; TFZ, Tacoma fault zone; SMFZ, Saddle Mountain fault zone; CRF, Canyon River fault zone. Source: USGS and Washington DNR.

Eastern Washington[12, 13, 14]

The state's two largest crustal earthquakes felt by European settlers occurred in Eastern Washington – the 1872 quake near Lake Chelan and the 1936 earthquake near Walla Walla. Residents of Spokane strongly felt a swarm of earthquakes in 2001; the largest earthquake in the swarm had a magnitude of 4.0.

The recent Spokane earthquakes were very shallow, with most events located within a few miles of the surface. The events occurred near a suspected fault informally called the Latah Fault; however, the relation between the fault and the swarm is uncertain. Geologists have mapped the Spokane area, but none confirmed the presence of major faults that might be capable of producing earthquakes. State geologists continue to investigate the local geology and earthquake risk in Spokane.

Elsewhere in Eastern Washington, geologists have uncovered evidence of a number of surface faults; however, they have not yet determined how active the faults are, nor determined the extent of the risk they pose to the public. One fault, Toppenish Ridge, appears to have been the source of two earthquakes with magnitudes of 6.5 to 7.3 in the past 10,000 years.

Forecasting Future Earthquakes[15]

The size of a fault segment, the stiffness of rocks, and the amount of accumulated strain energy combine to control the magnitude and timing of earthquakes. Fault segments most likely to break can be identified where faults and plate motions are well known.

If a fault segment is known to have broken in a past large earthquake, recurrence time and probable magnitude can be estimated based on fault segment size, rupture history, and accumulation of strain. Such a forecast, however, can be used only for well-understood faults, such as the San Andreas fault in California. No such forecasts can be made for poorly understood faults.

Faults in the Pacific Northwest are complex, and research on them is continuing. It is not yet possible to forecast when any particular fault in Washington State will break.

Earthquake Effects

Earthquakes cause damage by strong ground shaking and by the secondary effects of ground failures, tsunamis, and seiches. The strength of ground shaking generally decreases with distance from the earthquake source. Shaking can be much higher when soft soils amplify earthquake waves. West Seattle and downtown Olympia are examples where amplification repeatedly has occurred and ground shaking was much stronger than in other nearby areas.

Ground failures caused by earthquakes include fault rupture, ground cracking, lateral spreading, slumps, landslides, rock falls, liquefaction, localized uplift and subsidence.

Faults often do not rupture through to the surface. Unstable or unconsolidated soil is most at risk. Any of these failures will affect structures above or below them.

Large and disastrous landslides can often result from an earthquake. Liquefaction, which occurs when water-saturated soil loses its strength due to ground shaking, can cause building foundations to fail and low-density structures such as underground fuel tanks and pilings to float.

Tsunamis are waves that result from the displacement of the water column by changes in the sea floor, by landslides or submarine slides, or by volcanic explosions in the water. Seiches are standing waves in an enclosed or partially enclosed body of water (such as Lake Washington or Puget Sound) similar to sloshing waves in a bathtub. Historically, Washington has had minor damage from seiches. Seattle Fault and Cascadia subduction zone earthquakes, however, have caused tsunamis. Washington is also at risk from tsunamis from distant earthquakes (see the Tsunamis Hazard Profile, Tab 5.1.7 for more information on their impacts).

In terms of economic impact, Washington ranks second in the nation after California among states susceptible to economic loss caused by earthquake, according to a Federal Emergency Management Agency (FEMA) study. The study predicts that the state faces a probable annualized economic loss of $366 million due to earthquake; average annualized loss is an equivalent measure of future losses averaged on an annual basis. The Seattle-Tacoma-Bellevue area is fifth and Tacoma is 22nd on a list of metropolitan areas with more than $10 million in annualized earthquake losses.

Selected Earthquakes of Washington State, Magnitude 5.0 or Greater[16]

Date/Time (standard)	*Depth*	*Moment Magnitude*	*Location*
12/14/1872, 9:40 p.m.	0.0 km	6.8 (est.)	1.4 km SE of Chelan
01/11/1909, 3:49 p.m.	31.0 km	6.0	23.8 km NE of Friday Harbor
07/17/1932, 10:01 p.m.	0.0 km	5.7	15.6 km SE of Granite Falls
07/15/1936, 11:07 p.m.	0.0 km	6.1	8.1 km SSE of Walla Walla
11/12/1939, 11:45 p.m.	31.0 km	6.2	18.7 km S of Bremerton
04/29/1945, 12:16 p.m.	0.0 km	5.7	12.5 km SSE of North Bend
02/14/1946, 7:14 p.m.	25.0 km	5.8	28.4 km N of Olympia
04/13/1949, 11:55 a.m.	54.0 km	6.8	12.3 km ENE of Olympia
04/29/1965, 7:28 a.m.	57.0 km	6.7	18.3 km N of Tacoma
05/18/1980, 7:32 a.m.	2.8 km	5.7	1.0 km NNE of Mt St Helens

Selected Earthquakes of Washington State, Magnitude 5.0 or Greater[16]

Date/Time (standard)	*Depth*	*Moment Magnitude*	*Location*
02/13/1981, 10:09 p.m.	7.3 km	5.5	1.8 km N of Elk Lake
01/28/1995, 7:11 p.m.	15.8 km	5.0	17.5 km NNE of Tacoma
07/02/1996, 8:04 p.m.	4.3 km	5.4	8.5 km ENE of Duvall
07/02/1999, 6:44 p.m.	40.7 km	5.8	8.0 km N of Satsop
02/28/2001, 10:54 a.m.	51.9 km	6.8	17.0 km NE of Olympia
06/10/2001, 5:19 a.m.	40.7 km	5.0	18.3 km N of Satsop

Impacts caused by the earthquakes shaded in the table above are described in narratives below.

Lake Chelan – December 14, 1872[17]

The magnitude 6.8 (est.) earthquake occurred about 9:40 p.m.

This earthquake was felt from British Columbia to Oregon and from the Pacific Ocean to Montana. The location for this earthquake was most likely northeast of the town of Chelan. Because there were few man-made structures in the epicenter area near Lake Chelan, most of the information available is about ground effects, including huge landslides, massive fissures in the ground, and a 27-foot high geyser.

Extensive landslides occurred in the slide-prone shorelines of the Columbia River. One massive slide, at Ribbon Cliff between Entiat and Winesap, blocked the Columbia River for several hours. A field reconnaissance to the Ribbon Cliff landslide area in August 1976 showed remnants of a large landslide mass along the west edge of Lake Entiat (Columbia River Reservoir), below Ribbon Cliffs and about 3 kilometers north of Entiat. Although the most spectacular landslides occurred in the Chelan-Wenatchee area, slides occurred throughout the Cascade Mountains.

Most of the ground fissures occurred in the following areas: at the east end of Lake Chelan in the area of the Indian camp; in the Chelan Landing-Chelan Falls area; on a mountain about 12 miles west of the Indian camp area; on the east side of the Columbia River (where three springs formed); and near the top of a ridge on a hogback on the east side of the Columbia River. These fissures formed in several locations. Slope failure, settlements, or slumping in water-saturated soils may have produced the fissures in areas on steep slopes or near bodies of water. Sulfurous water was emitted from the large fissures that formed in the Indian camp area. At Chelan Falls, "a great hole opened in the earth" from which water spouted as much as 27 feet in the air. The geyser activity continued for several days, and, after diminishing, left permanent springs.

Reports of structural damage are limited because of the epicenter's remote location. Heavy damage occurred to a log building near the mouth of the Wenatchee River. Ground shaking threw people to the floor, wave ripples were observed in the ground, and loud detonations heard. About two miles above the Ribbon Cliff slide area, the logs on another cabin caved in.

Damaging ground shaking of intensity VI extended to the west throughout the Puget Sound basin and to the southeast beyond the Hanford Site. Individuals in Idaho, Montana, Oregon, and Canada felt the earthquake. Aftershocks occurred in the area for two years.

State-Line Earthquake – July 15, 1936[18, 1920]

The earthquake, magnitude 6.1, occurred at 11:05 a.m. The epicenter was about 5 miles south-southeast of Walla Walla. It was widely felt through Oregon, Washington and northern Idaho, with the greatest shaking occurring in Northeast Oregon. Property damage was estimated at $100,000 (in 1936 dollars) in this sparsely populated area.

The earthquake moved small objects, rattled windows, and cracked plaster in the communities of Colfax, Hooper, Page, Pomeroy, Prescott, Touchet, Wallula, and Wheeler; most of the impact and damage was in the Walla Walla area.

The earthquake alarmed residents of Walla Walla, many of whom fled their homes for the street. People reported hearing moderately loud rumbling immediately before the first shock. Standing pictures shook down, some movable objects changed positions, and doors partially opened. The earthquake was more noticeable on floors higher than the ground floor. It knocked down a few chimneys and many loose chimney brick; damaged a brick home used by the warden at the State Penitentiary that was condemned and declared unsafe; and damaged the local railroad station. Several homes moved an inch or less on their foundations, Five miles southwest of Walla Walla, the quake restored the flow of a weakened 600-foot deep artesian well to close to original strength; the flow had not diminished after several months.

Walla Walla residents reported about 15 or 20 aftershocks.

Olympia Earthquake – April 13, 1949[21, 22]

The earthquake, magnitude 6.8, occurred at 11:55 a.m. The epicenter was about eight miles north-northeast of Olympia, along the southern edge of Puget Sound. Property damage in Olympia, Seattle, and Tacoma was estimated at $25 million (in 1949 dollars); eight people were killed, and many were injured.

School buildings in widely separated towns were seriously damaged. Thirty schools serving 10,000 students were damaged; 10 were condemned and permanently closed. Chimneys on more than 10,000 homes required repair.

Water spouted from cracks that formed in the ground at Centralia, Longview, and Seattle. One new spring developed on a farm at Forest. Ground water, released by the shaking flooded several blocks of Puyuallup. Downed chimneys and walls were reported in towns throughout the area.

In Olympia, damage primarily was confined to the old part of the city and to areas of the port built on artificial fill. Most large buildings were damaged, including eight structures on the Capitol grounds. Many chimneys and two large smokestacks fell. Public utilities sustained serious damage; water and gas mains were broken and electric and telegraph services were interrupted. Breaks in 24 water mains temporarily closed the downtown business district.

In Centralia, the earthquake damaged 40 percent of the homes and businesses; two schools and a church were condemned; and the city's gravity-feed water system badly damaged. In Chehalis, damage occurred to four schools, city hall, the library, and county court house; the library was condemned. Seventy-five percent of the chimneys had to be replaced.

In Seattle, houses on filled ground were demolished, many old brick buildings were damaged, and chimneys toppled. One wooden water tank and the top of a radio tower collapsed. A 60-inch main broke at the city's water reservoir. Power failures occurred when swinging transmission lines touched, causing circuit breakers to trip. The gas distribution system broke at nearly 100 points, primarily due to damage caused by ground failure. Three damaged schools were demolished, and one rebuilt.

In Tacoma, many chimneys of older structures were knocked to the ground and many buildings were damaged. Water mains broke from landslides and settling in the Tideflats. Transformers at the Bonneville Power Administration substation were thrown out of alignment. Near Tacoma, a huge section of a 200-foot cliff toppled into Puget Sound three days after the earthquake that produced a tsunami that swept across Tacoma Narrows and reflected back to Tacoma, flooding a group of houses along the shoreline. South of Tacoma, railroad bridges were thrown out of alignment. A 23-ton cable saddle was thrown from the top of a Tacoma Narrows bridge tower, causing considerable damage.

The earthquake was felt in Idaho, Montana, Oregon, and in British Columbia, Canada. Only one small aftershock occurred during the next six months.

Seattle-Tacoma Earthquake – April 29, 1965[23, 24]

The earthquake, magnitude 6.7, struck the Puget Sound area at 7:28 a.m. The epicenter was about 12 miles north of Tacoma at a depth of about 40 miles. The earthquake caused about $12.5 million (in 1965 dollars) in property damage and killed seven people.

A rather large area of intensity VII ground shaking, and small pockets of intensity VIII ground shaking in Seattle and its suburbs, including Issaquah, characterized the quake. Pockets of intense ground shaking, seen in damage such as fallen chimneys, were associated with variations in the local geology.

In general, damage patterns repeated those observed in the April 1949 earthquake, although that event was more destructive. Buildings damaged in 1949 often sustained additional damage in 1965.

Most damage in Seattle was concentrated in areas of filled ground, including Pioneer Square and the waterfront, both with many older masonry buildings; nearly every waterfront building experienced damage. Eight schools serving 8,800 students were closed temporarily until safety inspections could be completed; two schools were severely damaged. Extensive chimney damage occurred in West Seattle. The low-lying and filled areas along the Duwamish River and its mouth settled, causing severe damage at Harbor Island; slumping occurred along a steep slope near Admiral Way. A brick garage partly collapsed at Issaquah; one school was damaged extensively; and chimneys in the area sustained heavy damage. Many instances of parapet and gable failure occurred. Damage to utilities in the area was not severe as in 1949.

Buildings with unreinforced brick-bearing walls with sand-lime mortar were damaged most severely. Multistory buildings generally had slight or no damage. However, the Legislative Building once again was damaged and temporarily closed; government activities moved to nearby motels. Performance of wood frame dwellings was excellent, with damage confined mainly to cracks in plaster or to failure of unreinforced brick chimneys near the roofline.

Also damaged were two electric transmission towers in a Bonneville Power Administration substation near Everett; the towers each supported 230,000-volt lines carrying power from Chief Joseph Dam to the substation. Three water mains failed in Seattle, and two of three 48-inch water supply lines broke in Everett.

The earthquake was felt in Idaho, Montana, Oregon, and in British Columbia, Canada; little aftershock activity was observed.

Nisqually Earthquake – February 28, 2001[25, 26]

Federal Disaster #1361. Stafford Act disaster assistance provided to date – est. $155.9 million. Small Business Administration disaster loans approved - $84.3 million. Federal Highway Administration emergency relief provided to date - $93.8 million.

The earthquake, magnitude 6.8, struck the Puget Sound area at 10:54 a.m. The epicenter was below Anderson Island near the Nisqually River delta in Puget Sound about 50 miles south of Seattle and 11 miles northeast of Olympia. Ground shaking lasted about 20 seconds. Two minor aftershocks occurred near the epicenter of the main shock. This event was a slab earthquake; its depth calculated at 32 miles below the earth's surface in the Juan de Fuca plate.

The area of most intense ground shaking occurred along the heavily populated north-south Interstate 5 corridor, not around the epicenter. This was due to the amplification of the earthquake waves on softer river valley sediments. The earthquake was felt over a large area – from Vancouver, British Columbia, to the north; to Portland, Oregon, to the south; and Salt Lake City, Utah, to the southeast.

The six counties most severely damaged by the earthquake – King, Kitsap, Lewis, Mason, Pierce, and Thurston – were declared federal disaster areas one day after the event. Eventually, 24 counties received disaster declarations for Stafford Act assistance.

Damages

Various estimates have placed damage to public, business and household property caused by the Nisqually earthquake at from $1 billion to $4 billion. A 2002 study by the University of Washington funded by the National Science Foundation estimated the quake caused $1.5 billion in damages to nearly 300,000 households. A second study, also by the University of Washington funded by the Economic Development Administration of the U.S. Department of Commerce, estimated that 20 percent of small businesses in the region affected by the quake had a direct physical loss and 60 percent experienced productivity disruptions.

Damage to buildings, bridges and lifelines varied across the region, and depended primarily on the local soil conditions and the distance from where the earthquake occurred. Damage to buildings, lifelines and bridges was mainly nonstructural, with the majority of structural damage occurring in unreinforced masonry buildings.

Severe damage occurred in Olympia, at SeaTac Airport, and in south Seattle in the Pioneer Square and Sodo areas. Structures damaged included office buildings, residences, schools, hospitals, airport facilities and churches. Many damaged structures and surrounding areas were closed for various lengths of time following the earthquake.

Structural damage was primarily concentrated in older, unreinforced masonry buildings built before 1950, with some damage reported to wood-frame structures and reinforced concrete structures. In general, new buildings and buildings that had recently been seismically upgraded typically displayed good structural performance, but many still sustained non-structural damage.

In the major urban areas of King, Pierce and Thurston counties, 1,000 buildings were rapidly assessed immediately following the earthquake. Of these, 48 buildings were red-tagged, indicating serious damage, and 234 were yellow-tagged indicating moderate damage.

Damaged significantly were several state government buildings in Olympia, including the Legislative Building (the state's Capitol Building). The dome of the 74-year-old building sustained a deep crack in its limestone exterior and damage to supporting columns. There was non-structural damage which occurred throughout the building. Most other state agency buildings closed for one or more days for inspection and repair.

Lifeline systems generally performed well during the event. Water utilities reported minor structural damages; a number of wells in Eastern Washington reportedly went dry. A gas-line leak caused a fire and explosion when two maintenance workers were resetting an earthquake valve at a correctional facility near Olympia. Seattle City Light reported 17,000 customer power outages, and Puget Sound Energy reported 200,000 customers without power, but power was restored to most customers within a day. The volume of calls placed immediately after the earthquake overloaded landline and wireless communication systems.

Transportation systems also suffered damage. Seattle-Tacoma International Airport closed immediately because its control tower was disabled. A temporary backup control tower allowed reopening of the airport to limited traffic several hours after the quake. King County Airport (Boeing Field) suffered serious cracking and gaps on the runway due to soil liquefaction and lateral spreading. The main runway reopened for business a week later.

While the area's overall road network remained functional, many highways, roads, and bridges were damaged. Several state routes and local roadways closed due to slumping and pavement fractures. The quake badly damaged the Alaskan Way Viaduct (State Route 99), a major arterial in Seattle. Temporary repairs made the structure usable; various proposals to permanently repair or replace it run in the billions of dollars. Two local bridges closed due to significant damage – the Magnolia Bridge in Seattle and the Fourth Avenue Bridge in Olympia.

There was minor damage to dock facilities in both Tacoma and Seattle, but not extensive enough to interrupt commercial port services.

The state's dams fared well during the earthquake. Of the 290 dams inspected by state engineers, only five had earthquake-related damage; these dams were susceptible to damage due to their poor construction and weak foundations. Dams controlled or regulated by the Federal Energy Regulatory Commission, the Bureau of Reclamation, or the U.S. Army Corps of Engineers, were not damaged.

Damage to residential structures came in a variety of forms, from severe mudslide destruction of entire homes to breakage of replaceable personal property. A 2002 University of Washington study on residential loss estimated nearly 300,000 residential units – about one of every four Puget Sound households – experienced $1.5 billion in damage. The study indicates that structural damage to roofs, walls and foundations accounted for nearly two-thirds of losses, followed by chimney damage, and damages to nonstructural elements and household contents.[27]

Jurisdictions Most Vulnerable

For the State Hazard Mitigation Plan, primary factors used to determine which counties are most vulnerable to future earthquakes are:

- The Annualized Earthquake Loss, as calculated by HAZUS-MH MR4.
- The Annualized Earthquake Loss Ratio, as calculated by HAZUS-MH MR4.

Counties considered most at risk are those with an Annualized Earthquake Loss of at least $1 million or with an Annualized Earthquake Loss Ratio equal or greater than the state's ratio of 0.04. Twenty-three counties meet one of these two criteria.

Additionally, Kittitas, Douglas, Franklin, and Walla Walla Counties, which have greater seismic risk than most counties in Eastern Washington but do not have building stock to meet the above criteria, have been added to the list of jurisdictions most vulnerable at the advice of state and federal geologists and seismologists with expertise in earthquakes in Washington.

Other factors, including the size of potentially vulnerable populations and age of the housing stock, also play a part in determining which counties are most vulnerable. Factors considered include:

- The percentage of the total population of each of the following groups: people who do not speak English as their primary language, individuals with disabilities, senior citizens, people living in poverty, and children in school (kindergarten through 12th grade.
- The percentage of housing stock built before 1960.

Based on these factors, the following counties are at greatest risk and most vulnerable to earthquakes:

Benton	Chelan	Clallam	Clark	Cowlitz	Douglas
Franklin	Grant	Grays Harbor	Island	Jefferson	King
Kitsap	Kittitas	Lewis	Mason	Pacific	Pierce
San Juan	Skagit	Skamania	Snohomish	Spokane	Thurston
Wahkiakum	Walla Walla	Whatcom	Yakima		

Counties Most Vulnerable and At-Risk to Earthquakes

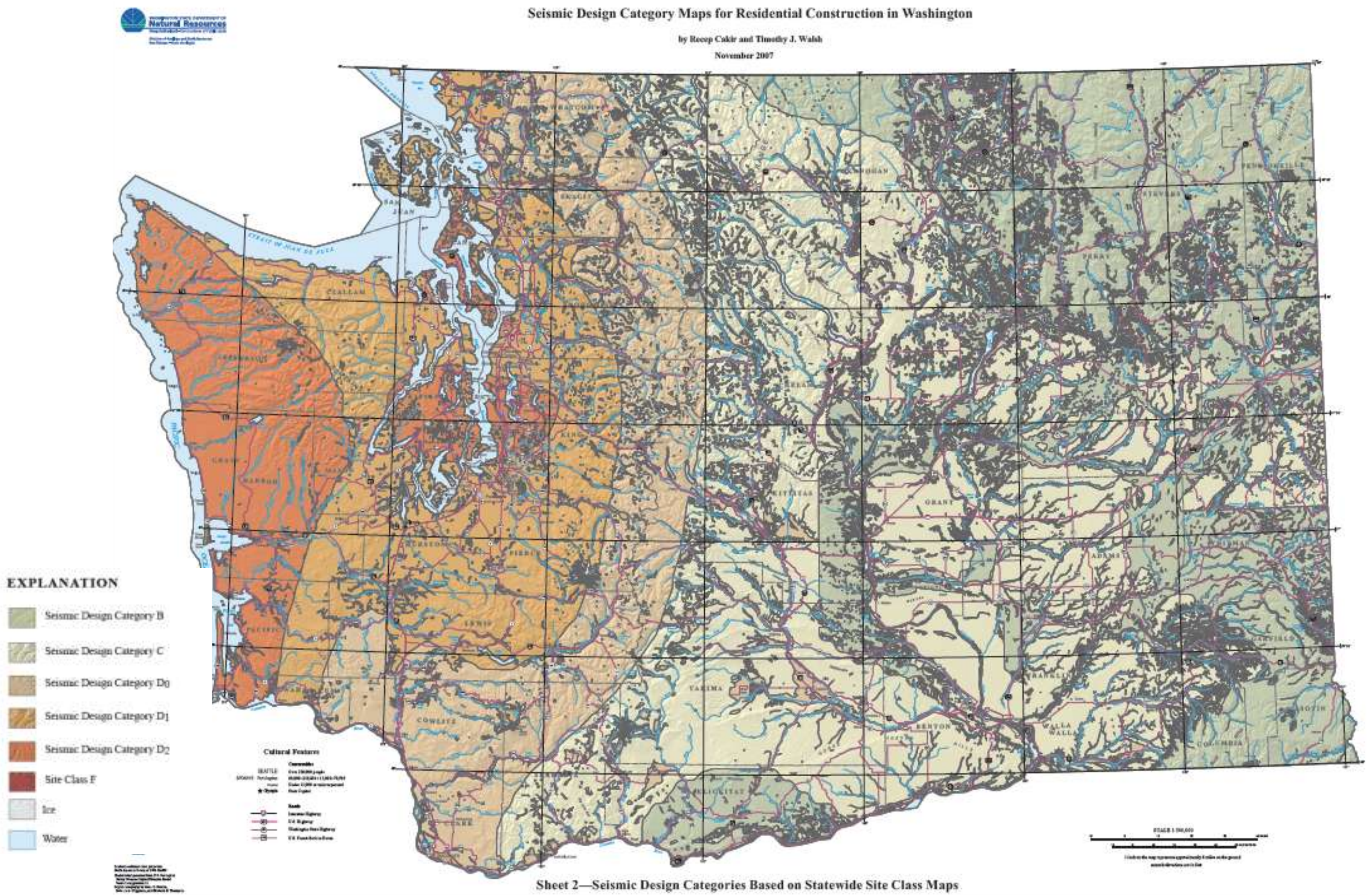


Figure 5. Seismic Design Category Map for Residential Construction in Washington State. The 2003 International Residential Code (2003 IRC)(International Code Council, 2003), was adopted by the Washington State Legislature as the official state building code for building one and two-family dwellings and townhouses. This map was created using the Washington State Department of Natural Resources Site Class map and the 2003 revisions of the USGS's 2002 short-period accelerations having a 2% probability of exceedance in 50 years. Source: http://listserv.wa.gov/cgi-bin/wa?A2=ind0803&L=geology-publications&P=69

Annualized Earthquake Loss and Annualized Earthquake Loss Ratio[28]

HAZUS-MH, a geographic information system (GIS) - based earthquake loss estimation tool developed by the Federal Emergency Management Agency (FEMA) in cooperation with the National Institute of Building Sciences (NIBS) was used to calculate the Annualized Earthquake Loss (AEL) and the Annualized Earthquake Loss Ratios (AELR) for the State of Washington. The Annualized Earthquake Loss addresses two key components of seismic risk: the probability of ground motion in terms of physical damage and economic loss. AEL also takes into account the regional variations in seismic risk. Annualized Earthquake Loss annualizes expected losses by averaging losses per return period (100; 250;500;750;1,000;1,500;2,000; and 2,500 years), which factors in historic patterns of smaller but more frequent earthquakes with those that are larger in magnitude but are infrequent in nature. This methodology enables the comparison of risk to occur between two geographic areas, such as Skagit County and Asotin County, WA. The Annualized Earthquake Loss values are presented on a per capita basis to allow for the comparison of the relative risk to earthquakes across regions based on population.

The Annualized Earthquake Loss Ratio is the Annualized Earthquake Loss presented as a fraction of the replacement value of the building inventory and is used for comparing the relative risk of a seismic event. Therefore, the annualized loss ratio allows for the relationship between the AEL and the building replacement values to be evaluated. This ratio can be used as a measure of relative risk between regions and within a state, since it is normalized by replacement value, allowing for the direct comparison across metropolitan areas, counties, and even between states.

The results of the HAZUS-MH calculated Annualized Earthquake Loss and Annualized Earthquake Loss Ratios are presented by county in Table 1, on page 22.

The Annualized Earthquake Loss and Ratios calculated using HAZUS-MH for each county in Washington State are not to be seen as determinations of total risk since not all aspects of earthquake are addressed. The value presented in Table 1 only represent the direct economic loss to buildings, and do not factor in such things as damage to lifelines and critical facilities and the indirect economic losses that can be sustained by communities and as a result of a seismic event. Also of note, the HAZUS-MH estimates annualized loss and annualized loss ratios were calculated using default inventory data for each county. This data is created from national datasets, and while it has improved over the years, the inventory can still differ dramatically from the inventory present in each county. Therefore, annualized earthquake loss and loss ratios calculated as part of a comprehensive risk study using updated inventory data and factoring in other components along with the direct economic loss to buildings, may differ in the values presented in Table 1.

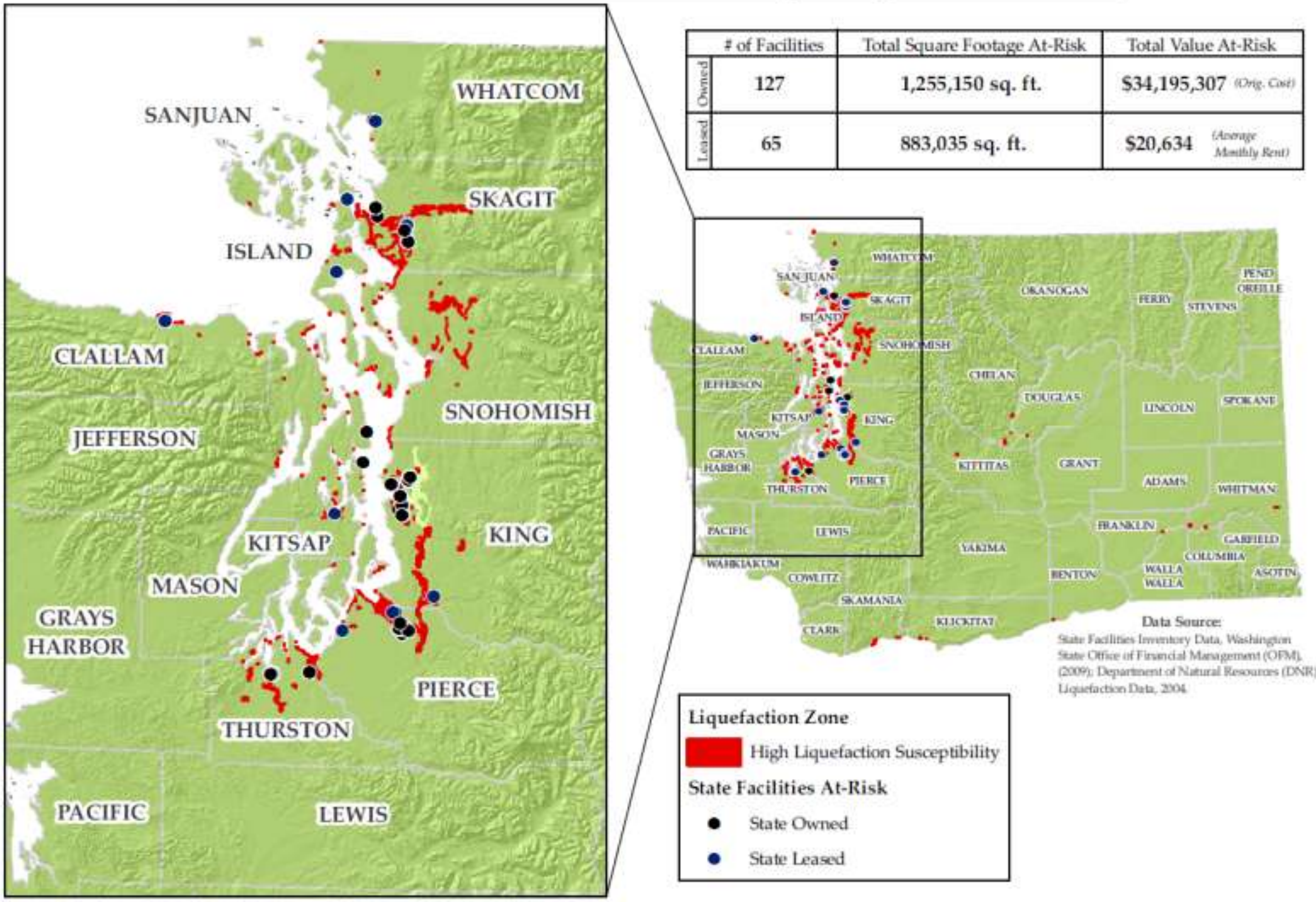
Table 1. Earthquake Annualized Loss Estimates from HAZUS-MH MR4

County	Total Annualized Loss	Loss Ratio	County	Total Annualized Loss	Loss Ratio
Grays Harbor	$8,900,797	0.11	Yakima	$6,243,098	0.03
Pacific	$2,861,631	0.09	Douglas	$654,151	0.02
Lewis	$7,009,144	0.09	Kittitas	$809,740	0.02
Wahkiakum	$353,077	0.08	Grant	$1,424,768	0.02
Cowlitz	$7,711,547	0.07	Chelan	$1,469,823	0.02
Clallam	$5,422,803	0.07	Franklin	$734,777	0.01
Mason	$3,841,874	0.07	Benton	$2,611,737	0.01
Kitsap	$18,119,926	0.07	Adams	$218,753	0.01
Jefferson	$2,300,227	0.06	Walla Walla	$824,767	0.01
King	$158,386,485	0.06	Okanogan	$477,392	0.01
Thurston	$15,635,612	0.06	Ferry	$83,027	0.01
Clark	$25,371,762	0.06	Lincoln	$125,645	0.01
Pierce	$49,904,156	0.06	Garfield	$33,713	0.01
Island	$5,263,710	0.06	Columbia	$48,044	0.01
Snohomish	$40,228,695	0.05	Spokane	$4,489,594	0.01
San Juan	$1,380,334	0.05	Whitman	$359,685	0.01
Skagit	$5,973,473	0.05	Stevens	$306,119	0.01
Skamania	$445,638	0.04	Pend Oreille	$97,341	0.01
Whatcom	$9,730,841	0.04	Asotin	$152,696	0.01
Klickitat	$552,683	0.03	***Washington State***	*$390,559,281*	*0.04*

Data Source: Earthquake Annualized Loss Estimates were run by the Washington State Military Department’s GIS Section using HAZUS-MH MR4 with default inventory data. Soils and liquefaction hazard maps produced by the Washington State Department of Natural Resources (DNR) were used in the analysis to supplement the default soils and liquefaction parameters traditionally assigned to the building inventory in HAZUS-MH.

State Owned & Leased Facilities in High Liquefaction Zones

	# of Facilities	Total Square Footage At-Risk	Total Value At-Risk
Owned	127	1,255,150 sq. ft.	$34,195,307 (Orig. Cost)
Leased	65	883,035 sq. ft.	$20,634 (Average Monthly Rent)



Socio-Economic Factors

The ability to prepare for and recover from a disaster varies among population groups. Research on various population groups and disasters found that some population groups are more vulnerable to the impact of a hazard event for a number of reasons. These population groups include people who do not speak English as their primary language, individuals with disabilities, senior citizens, people living in poverty, and children in school (pre-school through 12th grade).

- People who do not speak English as their primary language often have a language barrier that prevents them from getting the necessary data (in their language) which would keep them more fully informed. In some cases, this may hamper their abilities to prepare for a disaster, respond to a hazard event, or apply for assistance after a disaster.

- People with disabilities often have difficulties preparing in advance for a disaster because of hearing, sight, mobility, or mental impairments. This makes them less able to prepare in advance and more vulnerable to the impact of a hazard event than able-bodied individuals.

- Senior citizens may have trouble preparing for a disaster or recovering after a hazard event because some do not qualify for loans due to limited means, they have disabilities that limit their ability to prepare, or they may become disabled because of a hazard event.

- Economic levels also influence ones' ability to respond to and recovery from a disaster. Often times, low income housing is built in less safe areas and to basic code standards. Likewise, income levels also influence what type of housing they live in, whether they can engage in mitigation actions, and how long it takes to recover. People with limited financial means may not have money for preparedness or mitigation activities, and often live in older housing that is more vulnerable to a hazard event.

Counties with significant numbers of potentially vulnerable people are at greater risk to the impact of a disaster caused by an earthquake than counties with smaller populations from these groups.

Another factor considered in the vulnerability of counties to earthquake is age of their housing stock. The year housing was built is important for mitigation; the older a home is, the greater the risk of damage from natural disasters. Housing most at risk are those that have been built before 1960, when less stringent building codes were in place.

Table 2. Socio-Economic Factors Compared to State Average

County	Non-English Speaking	Disabled	Over Age 65	Poverty	K-12 Students	Housing Built Pre-1960
King	18.4%	15.1%	10.5%	6.4%	16.6%	33.5%
Pierce	11.8%	20.4%	10.2%	10.5%	20.3%	28.1%
Snohomish	12.2%	16.7%	9.1%	6.9%	20.2%	18.0%
Clark	11.5%	17.8%	9.5%	9.1%	20.5%	17.1%
Kitsap	8.3%	18.1%	10.6%	8.8%	20.2%	23.6%
Thurston	9.2%	18.9%	11.4%	8.8%	19.5%	16.9%
Grays Harbor	6.4%	24.0%	15.4%	16.1%	19.8%	41.8%
Whatcom	9.2%	14.3%	11.6%	14.2%	17.7%	26.0%
Grays Harbor	6.4%	24.0%	15.4%	16.1%	19.8%	41.8%
Cowlitz	6.0%	22.0%	13.3%	14.0%	19.8%	38.5%
Lewis	6.4%	24.2%	15.5%	14.0%	20.1%	36.9%
Yakima	31.8%	24.1%	11.2%	19.7%	23.8%	37.3%
Skagit	11.7%	18.2%	14.6%	11.2%	17.7%	30.6%
Clallam	6.3%	23.0%	21.3%	12.5%	17.1%	23.3%
Island	8.2%	16.5%	14.3%	7.0%	18.6%	17.0%
Spokane	6.6%	18.9%	12.4%	12.3%	19.3%	41.3%
Mason	6.3%	23.1%	16.5%	12.2%	18.5%	16.6%
Pacific	8.2%	26.3%	22.6%	14.2%	17.8%	36.2%
Benton	14.2%	17.9%	10.3%	10.3%	22.3%	26.0%
Jefferson	4.0%	16.3%	21.1%	12.5%	15.1%	21.3%
Chelan	19.6%	18.4%	13.9%	12.4%	21.5%	35.0%
Grant	28.3%	21.1%	11.6%	17.4%	23.4%	31.2%
San Juan	4.9%	16.4%	19.0%	9.2%	15.5%	14.0%
Walla Walla	16.2%	20.4%	14.8%	15.1%	19.1%	48.3%
Kittitas	7.7%	18.1%	11.6%	19.6%	15.6%	32.6%
Franklin	44.6%	23.7%	8.5%	19.2%	25.1%	29.1%
Douglas	19.5%	18.7%	12.7%	14.4%	22.3%	26.7%
Wahkiakum	4.3%	23.0%	18.5%	8.1%	18.0%	42.2%
Washington State	***14.0%***	***17.8%***	***11.2%***	***10.6%***	***19.1%***	***29.4%***

Source: U.S. Census Bureau, Profile of General Demographic Characters: 2000; Tables DP-1, DP-2, DP-3, and DP-4. [Source: http://censtats.census.gov/pub/Profiles.shtml]. Counties listed by ranking of annualized loss. Numbers expressed as the percentage of total population or total housing stock of each indicated county. Shaded cells indicate percentages of each factor that are greater than Washington State as a whole.

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